Earth's Hidden Mycorrhizal Superhighway: First Global High-Resolution Map Quantifies the Scale, Soil-Building Power, and Agricultural Vulnerability of Arbuscular Fungal Networks

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A landmark June 2026 study by the Society for the Protection of Underground Networks (SPUN) has produced the first high-resolution global map of arbuscular mycorrhizal (AM) fungal networks in the top 15 centimeters of soil. Utilizing over 16,000 soil cores, machine-learning models, and advanced robotic imaging, the research reveals 110 quadrillion kilometers of fungal filaments containing roughly 300 megatons of carbon. Connecting 70 percent of land plants, these networks sequester four billion tons of carbon dioxide annually, equivalent to 11 percent of global human fossil-fuel emissions. Through extensive hyphal growth and glomalin production, AM fungi actively engineer soil structure to enhance porosity, water retention, and nutrient access. However, conventional agricultural practices like tillage and heavy agrochemical applications reduce network densities by nearly half, severely undermining these natural soil-building processes. Fortunately, strategic and intentional inoculation offers a viable pathway for ecological restoration on degraded lands, though success depends on management choices. This comprehensive synthesis establishes a vital scientific baseline and practical roadmap, illustrating how protecting these hidden underground networks can significantly advance regenerative agriculture, grassland conservation, and global climate mitigation strategies.

Keywords: arbuscular mycorrhizal fungi, mycorrhizal networks, global mapping, soil carbon sequestration, glomalin, soil aggregation, regenerative agriculture, fungal inoculation, grassland ecosystems, agrochemical impacts, carbon drawdown, soil structure.

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1. Introduction to the Global Mapping Breakthrough

For most of human history, the vast majority of life on Earth has remained hidden from direct observation. Beneath the visible landscapes of forests, grasslands, and croplands lies an intricate web of fungal filaments that connects plant roots to the surrounding soil. These arbuscular mycorrhizal networks represent one of the oldest and most widespread symbioses on the planet, linking the physiology of approximately seventy percent of terrestrial plant species to the physical and chemical properties of the soil matrix. Until recently, scientists lacked the tools and data required to quantify this underground infrastructure at a truly global scale. Estimates of its extent relied on localized sampling, extrapolation, and indirect inference, leaving critical questions unanswered about total length, biomass, geographic distribution, and functional contributions to ecosystem processes.

In June 2026, an international research effort led by the Society for the Protection of Underground Networks produced the first high-resolution global map of arbuscular mycorrhizal fungal networks in the upper fifteen centimeters of soil. The study combined an unprecedented dataset of more than sixteen thousand soil cores collected from over four thousand locations across diverse biomes with advanced machine-learning models trained on environmental, climatic, and vegetation variables. Robotic imaging systems calibrated the models by measuring the diameter and length of more than three hundred thousand individual hyphae under controlled conditions. The resulting maps provide spatially explicit predictions of hyphal density at one-square-kilometer resolution for all vegetated land surfaces, excluding ice-covered regions and areas with insufficient sampling density.

The findings transformed previous understanding of scale. The networks comprise an estimated one hundred ten quadrillion kilometers of hyphal filaments containing approximately three hundred megatons of carbon. Annual carbon flux through these networks moves roughly four billion tons of carbon dioxide from plants into soil organic matter, a quantity equivalent to about eleven percent of annual anthropogenic emissions from fossil fuels. These figures position mycorrhizal fungi among the largest biological structures on Earth and among the most significant biological contributors to terrestrial carbon cycling.

Beyond raw magnitude, the mapping effort revealed pronounced geographic patterns. Network densities reach their highest values in grassland and wetland ecosystems, with notable concentrations in regions such as the Florida Everglades, the Tibetan Plateau, the Sudd wetlands of South Sudan, and North American tallgrass prairie landscapes. In contrast, intensively managed croplands exhibit densities approximately half those observed in comparable wild ecosystems, highlighting the sensitivity of these networks to modern agricultural practices. The spatial data also demonstrate that the majority of high-density areas currently lack formal

protection, raising questions about long-term resilience under continued land-use change and climate stress.

This breakthrough provides more than a static inventory. It supplies a quantitative foundation for understanding how mycorrhizal networks physically engineer soil structure through hyphal binding and the production of glomalin, how they mediate nutrient and water acquisition for plants, and how they contribute to long-term carbon stabilization. The maps also serve as a baseline against which future changes in land management, restoration efforts, and climate conditions can be measured. By rendering visible what had remained largely invisible, the 2026 global assessment opens new avenues for integrating biological soil processes into agricultural policy, conservation planning, and climate mitigation strategies.

The present analysis builds directly upon this foundational mapping. Subsequent sections examine the physical mechanisms by which mycorrhizal networks improve soil aggregation, porosity, and water dynamics; quantify their contributions to nutrient cycling and carbon sequestration; assess their vulnerability to tillage and agrochemical inputs; evaluate prospects for intentional inoculation on degraded lands; and consider implications for regenerative management of grassland and cropland systems. The discussion integrates the new global dataset with mechanistic understanding developed over decades of laboratory, field, and modeling research. The goal is to translate the newly quantified scale of Earth's mycorrhizal infrastructure into actionable insights for soil health, ecosystem resilience, and sustainable land use.

2. Scale and Quantification of Earth's Mycorrhizal Infrastructure

The 2026 global mapping effort delivered the first rigorous, spatially explicit quantification of arbuscular mycorrhizal fungal networks across Earth's vegetated land surface. Prior to this work, estimates of total hyphal length and biomass depended on limited field measurements extrapolated across broad biomes with substantial uncertainty. The new synthesis integrated direct observations from more than sixteen thousand soil cores with machine-learning predictions calibrated against robotic measurements of individual hyphal dimensions. This approach yielded internally consistent global totals that dramatically exceed earlier projections and establish mycorrhizal networks as one of the largest contiguous biological structures on the planet.

The total length of arbuscular mycorrhizal hyphae in the upper fifteen centimeters of soil is estimated at approximately one hundred ten quadrillion kilometers. When laid end to end, this length would encircle the Earth-Sun distance nearly one billion times. Such a figure places the combined hyphal network in the same order of magnitude as major geological or atmospheric

features when considered as a single biological entity. The networks are not uniformly distributed; however, the global integral provides a baseline against which regional variations and future changes can be assessed. Average hyphal densities in high-productivity grassland soils reach several meters per cubic centimeter, with localized measurements in optimal conditions exceeding ten meters of filament within a single teaspoon of soil. These densities translate into an extraordinarily fine-scale physical presence that permeates the soil matrix at scales relevant to both microbial processes and plant root function.

Biomass estimates derived from the same calibrated models indicate that the networks contain roughly three hundred megatons of carbon. This quantity represents four to six times the total living biomass of the entire human population. The figure refers specifically to the carbon contained within fungal tissues rather than the broader soil organic carbon pool influenced by fungal activity. Because hyphal turnover is relatively rapid in many environments, the standing biomass at any moment understates the cumulative carbon that passes through the networks over the course of a year. The mapping study estimated that plants transfer approximately four billion tons of carbon dioxide equivalent into soils annually through mycorrhizal pathways. This flux constitutes a meaningful fraction of terrestrial carbon cycling and underscores the networks’ role as a dynamic conduit rather than a static reservoir.

Derivation of these global numbers required careful attention to measurement and scaling. Robotic imaging platforms measured the diameter and length distributions of more than three hundred thousand living hyphae grown under standardized laboratory conditions. These empirical distributions allowed conversion of predicted hyphal length densities into biomass estimates while accounting for variation across fungal taxa and environmental conditions. Machine-learning models were trained on the combined dataset of soil cores and environmental covariates, with cross-validation and ensemble averaging used to reduce overfitting. Uncertainty estimates remain higher in undersampled regions such as parts of the tropics and high-latitude grasslands, yet the overall global totals are robust within the stated confidence bounds of the study.

The scale of the networks carries direct implications for soil physical properties. At average densities of several meters of hypha per cubic centimeter, the filaments occupy a non-negligible volume of the soil pore space and provide extensive surface area for interaction with mineral particles, organic matter, and water films. This physical presence underpins the networks’ capacity to bind soil aggregates and to access resources beyond the depletion zones of plant roots. The carbon contained within the hyphae themselves contributes to the slow-cycling fraction of soil organic matter once the filaments senesce, particularly through the production of glomalin and related compounds that resist rapid decomposition.

Comparisons with other planetary-scale biological features help contextualize the numbers. The total hyphal length exceeds the combined length of all roads and railways on Earth by several orders of magnitude. The annual carbon flux through the networks rivals the carbon uptake of entire major biomes when considered in isolation. These comparisons are not merely rhetorical; they indicate that any comprehensive model of terrestrial carbon cycling or soil formation must explicitly incorporate mycorrhizal dynamics at global scale. The 2026 mapping provides the quantitative scaffolding necessary for such integration.

Regional variation within the global totals reveals important ecological patterns. Grassland and wetland ecosystems account for a disproportionate share of both total length and biomass, consistent with the high root densities and favorable soil conditions that support extensive hyphal proliferation. In contrast, intensively managed croplands exhibit substantially lower standing lengths and biomass despite occupying large land areas. This contrast arises from both direct disturbance of hyphal networks through tillage and indirect suppression linked to high nutrient availability and chemical inputs. The global quantification therefore simultaneously highlights the magnitude of the intact system and the degree to which human land use has already reduced that magnitude in many regions.

The numbers reported here refer specifically to arbuscular mycorrhizal fungi in the top fifteen centimeters of soil. Deeper soil layers and other mycorrhizal types, particularly ectomycorrhizal networks associated with many temperate and boreal trees, add further length and biomass that remain outside the current global map. Future extensions of the mapping framework to greater depths and additional fungal guilds will likely increase the already impressive totals. Even within the present scope, however, the quantified infrastructure demonstrates that mycorrhizal networks constitute a planetary-scale biological system whose functional contributions to soil structure, nutrient cycling, and carbon storage warrant treatment as a major Earth-system process rather than a localized rhizosphere phenomenon.

Subsequent sections examine the mechanistic pathways through which this quantified infrastructure improves soil physical and chemical properties, the sensitivity of the networks to agricultural disturbance, and the prospects for deliberate management or restoration. The global scale established in this section provides the necessary context for evaluating both the current state of Earth’s mycorrhizal systems and the potential consequences of continued degradation or successful protection and enhancement.

3. Geographic Distribution, Hotspots, and Ecosystem Patterns

The global mapping of arbuscular mycorrhizal fungal networks reveals clear geographic structure in both total abundance and density. While the networks occur across virtually all

vegetated land surfaces, their standing length and biomass concentrate disproportionately in certain ecosystem types and regions. This uneven distribution arises from interactions among climate, soil properties, vegetation characteristics, and historical land use. Understanding these patterns is essential for identifying where the functional contributions of mycorrhizal networks to soil health and carbon cycling are greatest and where they face the highest risk of further degradation.

Grassland and wetland ecosystems emerge as the primary reservoirs of global mycorrhizal infrastructure. These systems collectively support approximately forty percent of the total estimated hyphal length and biomass despite occupying a smaller fraction of terrestrial land area than forests. Wild grasslands exhibit average hyphal densities roughly one-third higher than those found in moist tropical broadleaf forests, even though the latter support high aboveground productivity. The combination of dense fibrous root systems, moderate soil disturbance regimes, and favorable moisture and temperature conditions in many grasslands appears to favor extensive hyphal proliferation. Wetlands, particularly flooded grasslands, further amplify network development through periodic anoxic conditions that slow organic matter decomposition and maintain high levels of root and hyphal turnover.

Several regions stand out as exceptional hotspots of network density. The Florida Everglades support some of the highest predicted hyphal lengths per unit soil volume on the North American continent, reflecting the combination of wetland hydrology, warm temperatures, and diverse herbaceous vegetation. The Tibetan Plateau harbors extensive high-elevation grasslands with similarly elevated densities, likely sustained by cold-adapted plant communities and relatively low historical disturbance. In Africa, the Sudd wetlands and surrounding flooded grasslands of South Sudan represent another major concentration, where seasonal flooding and high plant productivity create conditions conducive to dense mycorrhizal networks. Within North America, the tallgrass prairies of the Flint Hills region and adjacent landscapes show notably high densities consistent with the broader pattern of grassland dominance. These hotspot areas share characteristics of relatively intact vegetation structure, limited tillage history, and soil conditions that support persistent hyphal growth.

In contrast, intensively managed croplands display systematically lower network densities across most regions. On average, agricultural landscapes exhibit hyphal lengths and biomass approximately half those observed in comparable wild or semi-natural ecosystems. This reduction stems from multiple interacting factors. Frequent tillage physically fragments hyphal networks and disrupts the continuity required for effective resource transport. High rates of synthetic phosphorus fertilization reduce plant dependence on mycorrhizal symbioses, leading to lower colonization rates and reduced hyphal investment. Certain agrochemicals, particularly fungicides and some herbicides, exert direct inhibitory effects on spore germination and hyphal

extension. The net result is a widespread depletion of mycorrhizal infrastructure in the very landscapes where soil health and nutrient retention are most critical for sustained productivity.

Tropical forest systems present a more nuanced picture. While moist broadleaf forests support substantial total network length due to their large land area, average densities per unit soil volume are generally lower than in grasslands. High phosphorus availability in many tropical soils, combined with rapid organic matter turnover and different root architectures, appears to limit the extent of extraradical hyphal development relative to grassland systems. Savanna and woodland transitions often show intermediate densities that reflect mixed vegetation and disturbance regimes. These patterns indicate that the functional importance of mycorrhizal networks varies systematically with ecosystem type rather than scaling simply with plant biomass or productivity.

The protection status of high-density areas raises additional concerns. The majority of regions identified as mycorrhizal hotspots currently lack formal conservation designation. This gap is particularly pronounced in grassland and wetland systems, which have historically received less protection than forests despite their disproportionate contribution to global mycorrhizal infrastructure. Conversion of grasslands to cropland continues at elevated rates in many regions, further fragmenting and reducing network extent. Because mycorrhizal networks require living host plants and relatively intact soil structure to persist, habitat conversion and intensive management produce long-lasting legacies even when agricultural use later ceases.

Climate and edaphic gradients also shape finer-scale distribution patterns. Network density tends to increase with moderate soil moisture and temperature regimes that support both plant growth and fungal activity. Extreme aridity or prolonged waterlogging can limit hyphal extension, although certain wetland-adapted fungal taxa thrive under periodic flooding. Soil texture influences outcomes as well; finer-textured soils with higher clay content often support greater hyphal proliferation and glomalin accumulation than coarse sands. These environmental relationships help explain why certain landscapes function as persistent hotspots while others support only sparse networks even under similar land-use histories.

The geographic patterns documented in the global map carry direct implications for ecosystem functioning and land management priorities. Areas of high network density represent locations where soil physical improvement, nutrient retention, and carbon stabilization are most strongly supported by biological processes. Conversely, regions where networks have been depleted through intensive agriculture may require targeted interventions to restore these functions. The spatial data also provide a baseline for monitoring future changes driven by climate shifts, land-use intensification, or restoration efforts. Because mycorrhizal networks operate at scales from individual roots to entire landscapes, their geographic distribution must be understood at multiple resolutions to inform effective conservation and agricultural strategies.

Subsequent sections examine the specific mechanisms through which these geographically variable networks improve soil structure, enhance nutrient and water relations, and contribute to carbon sequestration. The patterns established here indicate that protecting and restoring mycorrhizal infrastructure will yield the greatest returns in grassland and wetland systems while also offering substantial benefits in recovering agricultural landscapes. The uneven global distribution underscores both the current concentration of functional capacity in relatively intact ecosystems and the urgent need to reverse declines in managed lands where soil health is most directly linked to human well-being.

4. Mechanisms of Soil Physical Improvement

Mycorrhizal fungal networks exert direct physical effects on the soil matrix that extend far beyond their role as nutrient conduits. The extensive hyphal architecture and associated biochemical secretions actively reshape soil structure at scales ranging from individual aggregates to entire soil profiles. These physical modifications underpin many of the ecosystem services attributed to mycorrhizal systems, including improved water relations, reduced erosion, and enhanced long-term carbon stabilization. The global mapping effort demonstrated that regions with the highest network densities also exhibit the strongest expression of these physical benefits, while intensively managed landscapes with depleted networks show corresponding declines in soil structural quality.

The primary physical mechanism begins with the growth of extraradical hyphae through the soil pore network. These filaments, often only a few micrometers in diameter, thread between and around mineral particles and organic fragments. As hyphae proliferate, they mechanically enmesh soil components, creating a three-dimensional scaffolding that binds particles into larger, more stable units. This enmeshment effect operates continuously as the fungal network expands and turns over, providing a dynamic form of soil stabilization that responds to changes in plant activity and environmental conditions. In soils supporting dense networks, the cumulative surface area of hyphae can reach values that rival or exceed the surface area of the mineral fraction itself, greatly amplifying opportunities for physical interaction.

A second and equally important mechanism involves the production of glomalin and related glycoproteins by arbuscular mycorrhizal fungi. These compounds are secreted onto hyphal surfaces and into the surrounding soil, where they function as biological adhesives. Glomalin coats mineral particles and organic matter, promoting the formation of water-stable aggregates that resist slaking and dispersion during wetting and drying cycles. The proteinaceous nature of glomalin confers resistance to rapid microbial decomposition, allowing it to persist in soil for years to decades. This longevity distinguishes glomalin-mediated aggregation from more

transient binding mechanisms and contributes substantially to the maintenance of soil structure over time. Soils with high mycorrhizal activity typically accumulate measurable pools of glomalin-related soil protein that correlate strongly with aggregate stability indices.

The combined action of hyphal enmeshment and glomalin production generates a hierarchical aggregate structure. Primary particles and microaggregates are bound into larger macroaggregates that create a network of pores spanning multiple size classes. Large pores facilitate rapid water infiltration and gas exchange, while smaller pores within aggregates retain plant-available water against gravitational drainage. This dual porosity system improves both drainage during heavy rainfall and water retention during dry periods, buffering soil against extreme moisture fluctuations. In contrast, soils with reduced mycorrhizal networks often display degraded structure characterized by massive or platy horizons, reduced pore connectivity, and increased susceptibility to compaction and surface sealing.

These structural improvements translate directly into measurable enhancements in soil physical properties. Aggregate stability increases markedly in the presence of active mycorrhizal networks, reducing the formation of surface crusts and decreasing rates of water and wind erosion. The improved porosity enhances root penetration and proliferation, creating positive feedbacks that further support fungal colonization. Aeration within the soil profile improves, supporting aerobic microbial processes and reducing the risk of anaerobic conditions that can limit root function and nutrient availability. Over longer timescales, the accumulation of glomalin and other fungal-derived compounds contributes to the formation of stable soil organic matter fractions that reinforce structural stability.

The magnitude of these physical effects scales with network density. Landscapes supporting high hyphal lengths per unit soil volume, such as the grassland and wetland hotspots identified in the global map, exhibit correspondingly strong expression of aggregate stability and porosity benefits. In these systems, the continuous input of hyphal biomass and glomalin maintains structural quality even under moderate disturbance regimes. Conversely, the substantial reductions in network density observed in many cropland systems correspond to measurable declines in aggregate stability, increased erosion vulnerability, and degraded pore architecture. These differences help explain why soils under long-term conventional management often require greater mechanical intervention to maintain tilth and why restoration of biological activity can produce relatively rapid structural recovery when disturbance is reduced.

Water dynamics represent one of the most practically significant outcomes of mycorrhizal-mediated soil physical improvement. Enhanced aggregate stability and porosity increase infiltration rates during rainfall events, reducing surface runoff and associated nutrient losses. At the same time, the improved water-holding capacity within aggregates extends the period of plant-available moisture between rainfall or irrigation events. This dual benefit is particularly

valuable in regions experiencing increased climate variability, where both intense precipitation and prolonged dry spells are becoming more common. The physical infrastructure created by mycorrhizal networks therefore contributes to hydrological resilience at both field and watershed scales.

Erosion control follows directly from improved aggregate stability and infiltration. Soils with well-developed mycorrhizal networks resist detachment of particles during raindrop impact and overland flow. The binding action of hyphae and glomalin reduces the availability of fine particles that would otherwise be transported by wind or water. In grassland systems where network densities remain high, these effects help maintain soil cover and prevent the formation of rills and gullies. In agricultural contexts where networks have been depleted, the loss of these natural stabilizing mechanisms contributes to accelerated erosion rates and the need for external interventions such as cover cropping or reduced tillage to compensate.

The physical improvements generated by mycorrhizal networks also influence longer-term soil development processes. Stable aggregates protect organic matter from rapid decomposition by limiting microbial access and creating microenvironments with reduced oxygen diffusion. This protection contributes to the accumulation of soil organic carbon over decadal timescales. The same structural features that enhance water retention simultaneously slow the movement of dissolved nutrients and contaminants through the profile, reducing leaching losses. These coupled physical and biogeochemical effects demonstrate that mycorrhizal networks function as integrated soil engineers rather than isolated nutrient-exchange organs.

Subsequent sections examine how these physically improved soils interact with nutrient acquisition processes and carbon cycling dynamics. The structural foundation established by hyphal networks and glomalin creates the physical template within which the chemical and biological functions of mycorrhizal systems operate. Understanding this physical basis is essential for evaluating why regions with high network densities consistently display superior soil health metrics and why restoration of mycorrhizal activity often produces measurable improvements in soil tilth and resilience even before large changes in nutrient status become apparent. The global variation in network abundance documented earlier therefore corresponds to systematic differences in the physical quality of soils across Earth's major biomes and land-use types.

5. Nutrient Acquisition, Cycling Efficiency, and Plant Support

Mycorrhizal fungal networks fundamentally alter the nutrient economy of terrestrial ecosystems by extending the effective foraging range of plant roots and mediating the acquisition of resources that would otherwise remain inaccessible. The physical infrastructure quantified in

the global mapping creates a distributed absorption and transport system that operates continuously across the soil volume. This system enhances both the total quantity of nutrients obtained by plants and the efficiency with which those nutrients are retained and cycled within the ecosystem. The benefits are most pronounced for elements with low mobility in soil, particularly phosphorus, but extend to nitrogen, zinc, copper, and other micronutrients whose uptake is frequently limited by diffusion constraints.

The primary mechanism of enhanced acquisition lies in the extensive extraradical hyphal network that radiates outward from colonized roots. Individual hyphae explore soil pores and microsites far beyond the depletion zones that form around active root surfaces. Because hyphal diameters are orders of magnitude smaller than those of roots, the fungal network can penetrate fine-textured soils and access resources trapped in small pores or adsorbed onto clay surfaces. This spatial extension effectively multiplies the volume of soil from which a plant can draw nutrients without requiring proportional increases in root biomass. In many environments, the surface area available for nutrient absorption through the combined root-plus-hyphal system exceeds that of roots alone by factors of ten to one hundred.

Phosphorus acquisition illustrates the functional significance of this extended system. Phosphorus is highly immobile in most soils and rapidly forms insoluble complexes with iron, aluminum, and calcium. Mycorrhizal hyphae produce organic acids and phosphatases that solubilize bound phosphorus and transport the released ions back to the plant through the fungal cytoplasm. In many agricultural and natural systems, plants obtain the majority of their phosphorus requirement through mycorrhizal pathways rather than direct root uptake. This dependence becomes especially pronounced in low-phosphorus soils or under conditions where root growth is restricted. The global mapping shows that regions with the highest network densities, particularly grasslands, coincide with ecosystems where phosphorus limitation is common and where mycorrhizal mediation of phosphorus supply is therefore most critical.

Nitrogen dynamics also benefit from mycorrhizal networks, although the mechanisms differ from those governing phosphorus. Hyphae can access organic nitrogen forms and transport ammonium and nitrate ions efficiently across short distances. In addition, the improved soil structure created by hyphal binding and glomalin production enhances overall nitrogen retention by reducing leaching losses during heavy rainfall. The physical protection of organic matter within stable aggregates slows mineralization rates and maintains a more consistent supply of plant-available nitrogen over the growing season. These effects contribute to tighter nitrogen cycling within the ecosystem and reduce the environmental losses that frequently accompany high-input agricultural systems.

Micronutrient acquisition follows similar principles. Zinc, copper, and iron often exhibit low availability due to fixation or precipitation reactions in soil. The extensive hyphal network increases contact with microsites where these elements remain soluble and facilitates their transport to the host plant. In many cases, mycorrhizal plants maintain adequate micronutrient status under conditions where non-mycorrhizal plants develop deficiency symptoms. This capacity becomes particularly important in degraded or nutrient-poor soils where restoration efforts must overcome multiple simultaneous limitations.

The efficiency gains associated with mycorrhizal networks translate into reduced dependence on external nutrient inputs. Plants supported by well-developed fungal networks typically achieve comparable or superior growth with lower fertilizer applications than plants growing in depleted soils. This efficiency arises from both greater total uptake and improved internal allocation of acquired nutrients. The continuous turnover of hyphae also returns nutrients to the soil in forms that remain available to subsequent generations of roots and fungi, creating a more closed nutrient cycle within the rhizosphere and surrounding soil volume.

These acquisition and cycling benefits interact strongly with the physical improvements described in the previous section. Enhanced soil aggregation and porosity improve root and hyphal exploration while simultaneously reducing nutrient losses through leaching and erosion. The same glomalin that stabilizes aggregates also contributes to the slow release of bound nutrients as it gradually decomposes. This integration of physical and chemical functions means that mycorrhizal networks improve nutrient relations through multiple, mutually reinforcing pathways rather than through a single dominant mechanism.

Plant support extends beyond direct nutrient supply to include indirect benefits arising from improved nutritional status. Better phosphorus and micronutrient nutrition enhances root development, photosynthetic capacity, and overall plant vigor. These improvements increase resilience to abiotic stresses such as drought and temperature extremes. In addition, well-nourished plants often exhibit greater capacity to mount defensive responses against pathogens and herbivores, although the primary disease-suppression effects of mycorrhizal networks operate through competition and induced resistance mechanisms that operate alongside nutritional benefits.

The global distribution patterns documented earlier indicate that the nutrient-related functions of mycorrhizal networks are not uniformly expressed across all landscapes. Grassland and wetland hotspots support the highest densities of hyphae and therefore deliver the greatest per-unit-area contributions to nutrient acquisition and retention. In these systems, the networks help maintain productivity under relatively low external nutrient inputs, contributing to the characteristic stability and resilience of grassland ecosystems. In contrast, the substantial reductions in network density observed across much of the world's cropland correspond to

systems that have become increasingly dependent on synthetic fertilizers to compensate for diminished biological nutrient acquisition capacity.

Restoration of mycorrhizal networks on degraded agricultural land can therefore produce dual benefits of improved nutrient efficiency and reduced environmental losses. As network density recovers following adoption of reduced-tillage and diversified cropping practices, plants regain access to the extended foraging and transport system that characterizes intact ecosystems. This recovery can lower fertilizer requirements over time while simultaneously improving soil physical properties and carbon storage. The quantitative baseline provided by the global map allows such changes to be tracked and evaluated against regional benchmarks.

The nutrient functions of mycorrhizal networks also influence broader ecosystem processes. Tighter cycling of phosphorus and nitrogen reduces losses to waterways and the atmosphere, contributing to improved water quality and lower greenhouse gas emissions from agricultural soils. The same networks that enhance plant nutrition simultaneously support microbial communities that participate in nutrient transformations, creating a biologically integrated system for resource management. These interconnected effects demonstrate that mycorrhizal networks function as central hubs within the soil nutrient economy rather than as peripheral accessories to root activity.

Subsequent sections examine the carbon sequestration consequences of these nutrient and physical processes. The carbon allocated by plants to support mycorrhizal networks represents both an investment in nutrient acquisition and a direct contribution to soil organic matter formation. Understanding the linkages between nutrient dynamics and carbon cycling is essential for evaluating the full contribution of mycorrhizal infrastructure to ecosystem services and for designing management strategies that optimize multiple outcomes simultaneously. The global variation in network abundance established earlier provides the spatial context within which these integrated functions must be understood and managed.

6. Carbon Sequestration Dynamics and Long-Term Storage

Mycorrhizal fungal networks function as active participants in terrestrial carbon cycling rather than passive recipients of plant-derived carbon. The global mapping effort quantified both the standing carbon contained within the networks and the substantial annual flux of carbon moving from plants into soil through mycorrhizal pathways. These findings position arbuscular mycorrhizal fungi as significant contributors to soil carbon sequestration and long-term storage, with effects that operate through multiple interconnected mechanisms. The carbon dynamics of these networks link directly to the physical and nutrient functions examined in previous sections, creating integrated effects on soil health and ecosystem carbon balance.

Plants allocate a substantial portion of their photosynthetically fixed carbon to mycorrhizal fungi in exchange for enhanced nutrient and water acquisition. This allocation can represent a significant fraction of total plant carbon production, particularly in nutrient-limited environments where the benefits of the symbiosis are greatest. Once transferred to the fungal partner, carbon supports hyphal growth, maintenance, and reproduction. A portion of this carbon is rapidly respired by the fungus, while the remainder is incorporated into fungal biomass or released into the soil as exudates and cell wall components. The continuous nature of this carbon flow creates a steady input of organic material into the soil that would not occur in the absence of the mycorrhizal association.

Hyphal turnover represents a primary pathway for carbon entry into soil organic matter. Individual hyphae have relatively short lifespans compared with plant roots, leading to rapid production and decomposition cycles. As hyphae senesce, their structural components, including chitin and other polysaccharides, become available for incorporation into soil organic matter pools. This turnover contributes to both the labile and more stable fractions of soil carbon, depending on the chemical composition of the fungal tissues and the physical protection provided by the surrounding soil matrix. In ecosystems supporting high network densities, such as the grassland hotspots identified in the global map, the cumulative input from hyphal turnover constitutes a meaningful component of annual soil carbon inputs.

Glomalin and related glycoproteins produced by arbuscular mycorrhizal fungi play a particularly important role in long-term carbon stabilization. These compounds are deposited on hyphal surfaces and persist in soil long after the hyphae themselves have decomposed. Glomalin is relatively resistant to microbial degradation compared with many other forms of soil organic matter, allowing it to accumulate over time and contribute to stable carbon pools. The proteinaceous nature of glomalin also promotes its association with mineral surfaces, further enhancing its persistence. Soils with active mycorrhizal networks typically contain measurable quantities of glomalin-related soil protein that correlate with both aggregate stability and the size of the slow-cycling carbon fraction.

The physical improvements generated by mycorrhizal networks provide additional protection for carbon once it enters the soil. The same hyphal enmeshment and glomalin production that create stable aggregates also physically shield organic matter from rapid decomposition. Carbon located within the interior of water-stable aggregates experiences reduced oxygen availability and limited access by decomposer organisms, slowing mineralization rates. This physical protection mechanism operates synergistically with the chemical recalcitrance of glomalin, creating multiple barriers to carbon loss. In regions where network densities remain high, these combined physical and biochemical effects support greater accumulation of soil organic carbon over decadal timescales.

The global mapping quantified an annual carbon flux of approximately four billion tons of carbon dioxide equivalent moving from plants into soils through mycorrhizal pathways. This flux represents a substantial biological contribution to terrestrial carbon cycling and positions mycorrhizal networks as one of the more significant natural mechanisms for transferring atmospheric carbon into soil reservoirs. While not all of this carbon remains in the soil indefinitely, the portion stabilized through glomalin accumulation and aggregate protection contributes to long-term sequestration. The magnitude of the flux also indicates that changes in mycorrhizal network extent or activity, whether through land-use change or climate shifts, could produce measurable effects on regional and global carbon balances.

Land management practices exert strong influence over the carbon sequestration capacity of mycorrhizal networks. In grassland and wetland systems where network densities remain relatively intact, the continuous carbon allocation and stabilization processes support net carbon accumulation in soils. These ecosystems often function as important carbon sinks, with mycorrhizal activity contributing to both the quantity and stability of stored carbon. In contrast, the substantial reductions in network density observed across much of the world's cropland correspond to systems in which carbon inputs through mycorrhizal pathways have been diminished. Intensive tillage disrupts hyphal networks and exposes previously protected organic matter to decomposition, while high nutrient availability reduces plant allocation to fungal partners. The net result is a landscape in which the carbon sequestration potential of mycorrhizal networks has been substantially eroded.

Restoration of mycorrhizal networks on degraded agricultural land offers opportunities to recover carbon sequestration capacity. As network density increases following adoption of reduced disturbance and diversified management practices, plants resume greater carbon allocation to fungal partners. The resulting increase in hyphal turnover and glomalin production can accelerate the rebuilding of soil organic matter, particularly when combined with physical improvements in aggregate stability. These changes occur alongside improvements in nutrient efficiency and water relations, creating multiple co-benefits from the same biological infrastructure. The quantitative baseline established by the global map provides a reference against which such recovery trajectories can be evaluated.

The carbon dynamics of mycorrhizal networks also interact with broader ecosystem processes. Carbon stabilized through fungal activity influences soil fertility and structure over long timescales, creating feedbacks that support continued plant productivity and further carbon inputs. The same aggregates that protect carbon also improve water and nutrient retention, enhancing the conditions under which plants can maintain high rates of photosynthesis and allocation to mycorrhizal partners. These integrated effects demonstrate that mycorrhizal

networks function as central components of the terrestrial carbon cycle rather than as isolated participants.

Subsequent sections examine the sensitivity of these carbon-related functions to agricultural disturbance and evaluate prospects for deliberate management interventions. The global variation in network abundance and the associated differences in carbon flux and stabilization capacity provide the spatial framework within which management priorities must be established. Understanding how land-use decisions affect both the standing carbon contained within mycorrhizal networks and the annual flux of carbon moving through them is essential for developing strategies that simultaneously advance soil health and climate mitigation objectives. The mapping effort has made visible the scale at which these decisions operate and the magnitude of the biological system whose protection or restoration can influence carbon outcomes at meaningful scales.

7. Sensitivity to Tillage and Agrochemical Disturbance

Mycorrhizal fungal networks exhibit pronounced sensitivity to the dominant practices of conventional agriculture. The global mapping effort documented systematic and substantial reductions in network density across cropland landscapes relative to comparable wild ecosystems. These reductions arise from multiple interacting disturbance mechanisms that act on different components of the fungal life cycle and on the soil environment that supports network development. Understanding the specific pathways of impact is essential for evaluating the extent of current degradation and for identifying management changes that can support recovery of mycorrhizal function.

Tillage represents one of the most direct and pervasive physical disturbances to mycorrhizal networks. Repeated mechanical disruption of the soil profile severs hyphal connections, fragments the three-dimensional network architecture, and exposes previously protected hyphae to desiccation and microbial attack. Because arbuscular mycorrhizal fungi rely on continuous hyphal growth and anastomosis to maintain functional networks, frequent tillage prevents the establishment of extensive extraradical mycelium. The physical effects are compounded by changes in soil structure; tillage often destroys the very aggregates that mycorrhizal activity helps to create, creating a negative feedback loop that further limits fungal proliferation. In landscapes subject to annual or multiple annual tillage operations, the standing network is repeatedly reset, preventing the accumulation of the dense hyphal mats observed in untilled grassland and wetland systems.

Agrochemical inputs exert both direct and indirect effects on mycorrhizal fungi. Fungicides, by design, target fungal organisms and frequently inhibit spore germination, hyphal extension, and

root colonization by arbuscular mycorrhizal species. The impact varies with active ingredient, application rate, and timing, but many commonly used products produce measurable suppression of mycorrhizal activity even at recommended field rates. Herbicides can affect mycorrhizal fungi both directly through toxicity to spores and hyphae and indirectly by altering plant physiology and reducing the quality or quantity of carbon allocated to fungal partners. Some herbicides have been shown to reduce colonization rates and spore viability, with effects that can persist beyond the period of active weed control. Insecticides generally produce smaller direct impacts on mycorrhizal fungi, although certain compounds may influence soil microbial communities in ways that indirectly affect fungal performance.

High rates of synthetic phosphorus fertilization constitute a particularly important form of indirect suppression. When plants receive abundant readily available phosphorus, they downregulate investment in mycorrhizal symbioses, resulting in lower colonization rates and reduced development of extraradical hyphae. This response is an evolved regulatory mechanism that conserves plant carbon when the nutritional benefits of the symbiosis are diminished. In intensively managed systems where phosphorus is applied in excess of crop demand, the soil environment becomes less favorable for mycorrhizal network development even in the absence of direct toxicity. The combination of high nutrient availability and frequent disturbance creates conditions under which mycorrhizal fungi persist at low levels but fail to develop the extensive networks characteristic of low-input ecosystems.

The global mapping quantified the cumulative outcome of these disturbance mechanisms. Cropland landscapes exhibit average hyphal densities and biomass approximately half those observed in comparable wild grasslands and wetlands. This reduction is widespread across major agricultural regions and represents a substantial depletion of the biological infrastructure that supports soil physical improvement, nutrient acquisition, and carbon stabilization. The magnitude of the decline indicates that conventional management practices have fundamentally altered the mycorrhizal component of soil biological communities across large portions of the Earth’s agricultural land base.

These reductions in network density carry direct consequences for soil function and ecosystem services. Soils with depleted mycorrhizal networks exhibit lower aggregate stability, reduced porosity, and diminished capacity for water retention and infiltration. Nutrient acquisition efficiency declines, increasing dependence on external fertilizer inputs and elevating the risk of nutrient losses to the environment. Carbon sequestration potential is reduced both through lower inputs via hyphal turnover and glomalin production and through greater exposure of existing soil organic matter to decomposition following aggregate disruption. The combined effects contribute to the progressive degradation of soil health observed in many long-term

conventional farming systems and help explain the increasing external inputs required to maintain productivity.

The sensitivity of mycorrhizal networks to disturbance also implies long-term legacies. Once networks are depleted, recovery requires both the re-establishment of fungal populations and the restoration of soil conditions that support extensive hyphal growth. In the absence of living host plants or under continued high-disturbance regimes, fungal populations can decline to levels from which natural recolonization proceeds slowly. This legacy effect means that even when management changes are implemented, full recovery of mycorrhizal function may require multiple growing seasons and depends on the severity and duration of prior disturbance.

The global patterns documented in the mapping effort reveal that the impacts of conventional agriculture are not uniformly distributed. Regions with longer histories of intensive tillage and high agrochemical use show more pronounced reductions in network density. Conversely, areas where grassland or perennial vegetation has been maintained, or where reduced-tillage practices have been adopted more recently, retain higher residual network densities that can serve as nuclei for recovery. These spatial differences provide guidance for prioritizing restoration efforts and for identifying management systems that minimize further degradation of mycorrhizal infrastructure.

Subsequent sections evaluate the potential for intentional inoculation to accelerate recovery on degraded lands and examine the broader implications of mycorrhizal decline and restoration for regenerative agricultural systems. The sensitivity of these networks to tillage and agrochemical disturbance underscores the importance of management practices that protect existing biological infrastructure while creating conditions favorable for network expansion. Because the physical, nutrient, and carbon-related functions of mycorrhizal networks depend on adequate density and connectivity, the reductions documented across global croplands represent a significant constraint on the capacity of agricultural soils to deliver multiple ecosystem services simultaneously. Addressing this constraint requires management approaches that explicitly account for the biological requirements of mycorrhizal fungi as central components of soil health.

8. Potential and Limitations of Intentional Inoculation

Intentional inoculation with arbuscular mycorrhizal fungi represents a targeted intervention to restore or enhance network function on lands where native populations have been depleted or where rapid establishment is desired. The practice builds on the recognition that mycorrhizal networks require living fungal propagules and compatible host plants to develop. While inoculation cannot instantly recreate the dense, continuous networks observed in long-

undisturbed ecosystems, it can accelerate colonization and provide a foundation for subsequent network expansion under favorable management conditions. The global mapping effort identified extensive areas of reduced network density, particularly in cropland landscapes, where inoculation combined with appropriate management changes offers a practical pathway toward recovery.

Commercial inoculants typically contain spores, hyphal fragments, or colonized root pieces of selected arbuscular mycorrhizal species, often formulated as powders, granules, or liquids. Application methods are designed to place propagules in close proximity to developing roots. Seed treatments coat planting material with inoculant prior to sowing, ensuring early contact between emerging roots and fungal propagules. In-furrow or banded applications deliver inoculant directly into the seed zone during planting operations. For transplanted crops, seedlings, or trees, root dips or incorporation into potting or transplant media provide targeted delivery. On existing vegetation or restoration sites, inoculants can be top-dressed, mixed into surface soil, or injected into the profile, although success depends on subsequent root growth into the treated zone.

The effectiveness of inoculation varies with environmental conditions and management context. Inoculation tends to produce the greatest benefits in situations where native mycorrhizal populations are low or absent. These conditions commonly occur in severely disturbed soils, such as those following mining, construction, or long-term intensive tillage; in sterile potting mixes used for container production; and in fumigated or heavily sterilized field soils. New plantings on former agricultural land or restoration sites with depleted biological legacies also frequently respond positively. In contrast, soils that already support diverse and abundant native mycorrhizal communities often show limited additional response to introduced inoculants, as the resident fungi can outcompete or complement the introduced strains.

Soil chemical and physical conditions strongly influence inoculation outcomes. High levels of available phosphorus suppress colonization by both native and introduced fungi, reducing the benefit of inoculation unless phosphorus inputs are simultaneously reduced. Soil temperature and moisture during the critical establishment period affect spore germination and hyphal growth; most arbuscular mycorrhizal species perform best within moderate temperature and moisture ranges. Soil pH and texture also play roles, with some fungal taxa showing preferences for particular edaphic conditions. Successful inoculation therefore requires attention to site-specific factors and, in some cases, selection of fungal strains adapted to local conditions.

The timeline from inoculation to functional network development spans multiple scales. Initial root colonization can begin within days to a few weeks under favorable conditions, as germinating spores or active hyphae contact susceptible root tissues and form arbuscules. Early extraradical hyphal growth extends the network into the surrounding soil over subsequent

weeks. Measurable improvements in plant nutrient status and growth often become apparent within the first growing season. However, the development of dense, interconnected networks capable of delivering substantial soil physical and carbon-related benefits typically requires longer periods. Significant accumulation of glomalin and measurable improvements in aggregate stability generally emerge over one to several years as hyphal turnover and glomalin deposition proceed. Full landscape-scale effects depend on the rate of network expansion through root-to-root connections and the maintenance of conditions that support continued fungal activity.

Several limitations constrain the outcomes of inoculation programs. Introduced fungi must compete with any residual native populations and with the broader soil microbial community. Success is not guaranteed, and field results can vary substantially between sites and years. Inoculation represents an input cost that must be justified by subsequent benefits in yield, input savings, or soil improvement. The practice does not substitute for management changes that address the underlying causes of network depletion. Continued high tillage intensity, excessive phosphorus fertilization, or repeated fungicide applications can limit or reverse gains achieved through inoculation. In addition, the genetic diversity and functional traits of commercial inoculants may not fully match the complexity of native communities that have developed over long periods under local conditions.

Despite these limitations, inoculation can serve as a valuable component of integrated soil restoration strategies when applied thoughtfully. On degraded agricultural land transitioning to reduced-tillage or diversified systems, inoculation can accelerate the re-establishment of mycorrhizal function during the critical early years when native populations are recovering. In restoration of grasslands or other perennial systems on former cropland, inoculation supports faster development of the biological infrastructure that contributes to soil aggregation, nutrient retention, and carbon stabilization. In high-value horticultural or perennial crop systems, targeted inoculation of transplants can improve establishment success and early growth, particularly in fumigated or container-grown material.

The potential of inoculation is greatest when combined with management practices that protect and support network development after introduction. Reduced tillage preserves hyphal continuity and allows networks to expand. Cover crops and diverse rotations provide continuous host plants and varied root architectures that support different fungal taxa. Reduced reliance on high phosphorus fertilizers and broad-spectrum fungicides removes major constraints on fungal activity. When these supporting practices are in place, inoculation can initiate a positive feedback loop in which improving soil conditions and plant vigor further enhance mycorrhizal performance.

The global mapping of network densities provides a spatial framework for identifying where inoculation interventions are likely to yield the highest returns. Regions showing the most pronounced reductions relative to potential, particularly former grassland areas now under intensive management, represent priority landscapes for combined inoculation and management change. The quantitative baseline also allows monitoring of recovery trajectories following inoculation and associated practice changes, enabling adaptive management based on observed progress toward benchmark densities.

Subsequent sections examine the broader implications of mycorrhizal restoration for regenerative agricultural systems and consider how inoculation fits within comprehensive strategies for soil health improvement. The limitations of inoculation underscore that biological soil functions are best supported through ongoing management rather than through one-time interventions alone. When used as part of a coherent approach that addresses disturbance, nutrient management, and plant diversity, inoculation can contribute meaningfully to rebuilding the mycorrhizal infrastructure whose scale and functional importance have been revealed by global mapping. The practice therefore represents one practical tool among several for translating the scientific understanding of mycorrhizal networks into improved outcomes for soil, crops, and ecosystems.

9. Implications for Regenerative Agriculture and Land Restoration

The global quantification of arbuscular mycorrhizal fungal networks provides a scientific foundation for understanding how regenerative agricultural practices and land restoration efforts can rebuild critical soil biological infrastructure. Conventional management has substantially reduced network densities across large areas of cropland, diminishing the physical, nutrient, and carbon-related functions that these networks support. Regenerative approaches that minimize disturbance, enhance plant diversity, and reduce reliance on synthetic inputs create conditions under which mycorrhizal networks can recover and expand. This recovery in turn reinforces the soil health improvements that regenerative systems seek to achieve, generating positive feedbacks between biological activity and ecosystem function.

Reduced tillage or no-till systems represent one of the most direct ways to protect and restore mycorrhizal networks. By limiting mechanical disruption of hyphae, these practices allow existing networks to persist and expand through root-to-root connections and hyphal growth. Over multiple seasons, continuous hyphal networks develop that support efficient nutrient transport and contribute to aggregate formation. The physical protection of soil structure also reduces exposure of organic matter to decomposition, supporting carbon accumulation. In landscapes where tillage has been the dominant cause of network depletion, the transition to

reduced tillage often produces measurable increases in mycorrhizal colonization and hyphal density within a few growing seasons.

Cover crops and diversified rotations further enhance mycorrhizal performance by providing continuous living roots and varied host plants. Different plant species support different fungal taxa, increasing overall community diversity and functional redundancy. Cover crops extend the period of active photosynthesis and carbon allocation to soil organisms, sustaining fungal activity during periods when main crops are absent. Diverse rotations also disrupt pest and disease cycles that might otherwise require chemical interventions harmful to mycorrhizal fungi. The combination of reduced tillage and diversified plant communities creates a soil environment in which mycorrhizal networks can develop the density and connectivity observed in less disturbed grassland systems.

Reductions in synthetic phosphorus fertilization and broad-spectrum fungicide use remove major constraints on mycorrhizal activity. When plants receive high levels of readily available phosphorus, they downregulate investment in fungal symbioses. Lowering phosphorus inputs to levels closer to crop demand encourages greater colonization and hyphal development. Similarly, minimizing fungicide applications preserves spore viability and hyphal function. These changes do not require complete elimination of external inputs but rather a recalibration toward rates and timings that allow biological nutrient acquisition mechanisms to operate effectively. Integrated approaches that combine biological and judicious synthetic inputs often achieve comparable or superior yields while supporting greater mycorrhizal activity.

The functional outcomes of mycorrhizal recovery under regenerative management include improvements across multiple soil health indicators. Enhanced aggregate stability and porosity improve water infiltration, retention, and aeration. Better nutrient acquisition efficiency reduces the quantity of external fertilizers needed to achieve target yields and lowers the risk of nutrient losses to the environment. Increased carbon inputs through hyphal turnover and glomalin production contribute to soil organic matter accumulation, which further reinforces structural stability and nutrient retention. These interconnected improvements create more resilient cropping systems capable of maintaining productivity under variable weather conditions.

Carbon sequestration represents a particularly significant co-benefit of mycorrhizal recovery in regenerative systems. The annual flux of carbon through mycorrhizal pathways documented in the global mapping indicates that increases in network density and activity can meaningfully enhance soil carbon storage. Regenerative practices that support higher network densities simultaneously increase carbon inputs via hyphal turnover and improve the physical protection of organic matter within stable aggregates. These effects operate alongside other carbon-building mechanisms such as reduced tillage and increased root biomass from cover crops and

perennials. The combined result is a management system that advances both soil health and climate mitigation objectives.

Water resilience and erosion control improve as mycorrhizal networks recover. Enhanced aggregate stability reduces surface sealing and crusting, increasing infiltration during intense rainfall events. Improved porosity and water-holding capacity within aggregates extend the period of plant-available moisture during dry spells. Reduced erosion follows from greater aggregate stability and better infiltration, protecting soil resources and reducing sediment and nutrient transport to waterways. These hydrological benefits are especially valuable in regions experiencing greater climate variability, where both flooding and drought risks are increasing.

Economic considerations influence the adoption of practices that support mycorrhizal networks. Reduced tillage can lower fuel and labor costs while improving soil workability over time. Lower fertilizer requirements, achieved through improved biological acquisition efficiency, reduce input expenses. Yield stability under variable weather can improve farm resilience and reduce risk. However, transitions to regenerative systems often involve short-term challenges, including potential yield dips during the period when soil biology is rebuilding and the need for new equipment or management skills. Successful transitions typically combine multiple supportive practices rather than relying on any single change, and they benefit from technical support and peer learning networks.

Land restoration efforts on former agricultural or degraded sites also benefit from attention to mycorrhizal networks. Conversion of cropland back to grassland or prairie vegetation creates opportunities for network recovery, particularly when combined with reduced disturbance and diverse plantings. Inoculation can accelerate establishment on sites with very low residual fungal populations. Mine reclamation, construction site restoration, and other severely disturbed landscapes often require deliberate introduction of mycorrhizal fungi alongside appropriate plant species to initiate soil biological recovery. The physical and carbon-related functions supported by recovering networks contribute to long-term site stability and ecosystem development.

The global mapping provides a reference framework for evaluating progress in both agricultural and restoration contexts. Regions that currently show low network densities relative to their potential can be prioritized for regenerative transitions or active restoration. Monitoring changes in network indicators over time allows assessment of whether management changes are producing the desired biological recovery. Because mycorrhizal functions integrate physical, chemical, and biological aspects of soil health, improvements in network density and activity serve as integrative indicators of overall progress toward regenerative outcomes.

The implications extend beyond individual fields or farms. Widespread adoption of practices that support mycorrhizal networks can contribute to landscape-scale improvements in soil health, water quality, and carbon storage. These changes align with broader societal goals for sustainable food production and climate mitigation. The scientific understanding of mycorrhizal networks as a planetary-scale biological infrastructure, now quantified through global mapping, provides both the rationale and the metrics for integrating biological soil management into agricultural and land-use policy. Regenerative approaches that explicitly account for mycorrhizal function represent a practical translation of this understanding into management systems capable of delivering multiple environmental and productive benefits simultaneously.

10. Relevance to Grassland and Prairie Ecosystems

Grassland and prairie ecosystems occupy a disproportionately important position in the global distribution of arbuscular mycorrhizal fungal networks. Although these systems cover a smaller total land area than forests, they support approximately forty percent of the world's estimated mycorrhizal infrastructure. This concentration arises from the combination of dense fibrous root systems, relatively stable soil environments, and disturbance regimes that favor extensive hyphal development. The global mapping effort identified grasslands and wetlands as the primary reservoirs of both standing hyphal length and annual carbon flux through mycorrhizal pathways, establishing these ecosystems as critical components of planetary soil health and carbon cycling.

Several characteristics of grassland vegetation and soils create conditions particularly favorable for mycorrhizal network development. Perennial grasses produce extensive fine root systems that provide abundant colonization sites and continuous carbon allocation to fungal partners. Moderate levels of grazing and fire, which historically shaped many grassland ecosystems, maintain plant community diversity without the severe soil disruption associated with tillage. Soil moisture regimes in many grasslands support active fungal growth for extended periods, while the accumulation of organic matter from root turnover creates a favorable substrate for hyphal proliferation. These factors interact to produce the high network densities observed in grassland hotspots worldwide.

Within North America, the tallgrass prairies represent a regionally significant concentration of mycorrhizal infrastructure. The Flint Hills and adjacent prairie landscapes support notably high hyphal densities consistent with the broader pattern of grassland dominance. These systems developed under a combination of climatic conditions, fire regimes, and grazing pressure that maintained diverse herbaceous plant communities and relatively intact soil profiles. The resulting mycorrhizal networks contribute to the characteristic resilience of tallgrass prairie

soils, including their capacity for water retention, nutrient cycling, and resistance to erosion. Similar patterns occur in other grassland regions identified as hotspots, including portions of the Tibetan Plateau and African savanna and wetland systems.

The functional contributions of mycorrhizal networks in grasslands extend across multiple ecosystem processes. High network densities support efficient nutrient acquisition under conditions where phosphorus and other elements may be limiting, helping maintain plant productivity without large external inputs. The physical improvements in soil structure generated by hyphal activity and glomalin production enhance water infiltration and retention, contributing to drought resilience in environments that experience significant seasonal moisture variability. Carbon inputs through hyphal turnover and stabilization via glomalin accumulation support the relatively high soil organic matter levels characteristic of many grassland soils. These integrated functions help explain the long-term stability and productivity of grassland ecosystems under historical disturbance regimes.

Contemporary threats to grassland mycorrhizal infrastructure are substantial. Conversion of native grasslands to cropland represents the most direct and widespread impact, replacing perennial vegetation and relatively undisturbed soils with annual crops and frequent tillage. This transition produces the large reductions in network density observed across global cropland landscapes. Overgrazing, invasive species, and altered fire regimes can further degrade plant community composition and soil conditions in remaining grasslands, indirectly affecting mycorrhizal communities. Climate change introduces additional stressors through shifts in temperature and precipitation patterns that may alter the balance between plant hosts and fungal partners.

Conservation of existing high-density grassland systems offers the most effective strategy for preserving mycorrhizal infrastructure at scale. Protected areas that maintain native plant communities and natural disturbance regimes support the continuous operation of mycorrhizal networks and their associated soil-building and carbon sequestration functions. Because the majority of identified mycorrhizal hotspots currently lack formal protection, expanding conservation efforts in grassland regions represents a high-priority opportunity. Even partial protection or improved management of working grasslands can help maintain network function while supporting agricultural or pastoral livelihoods.

Restoration of grasslands on former cropland or degraded sites provides opportunities to rebuild mycorrhizal networks in areas where they have been substantially reduced. Re-establishment of perennial vegetation, particularly diverse native plant communities, creates the host plants and root systems necessary for fungal recolonization. Reduced tillage or no-till establishment methods minimize further disruption during the critical early phases of restoration. In severely depleted sites, inoculation with appropriate fungal strains can accelerate

initial colonization, although long-term network development depends on the re-creation of favorable soil and plant community conditions. Successful grassland restoration simultaneously advances multiple objectives, including soil health recovery, carbon sequestration, biodiversity conservation, and watershed protection.

The relevance of grassland and prairie systems extends beyond their direct contribution to global mycorrhizal totals. These ecosystems often occur in landscapes where soil conservation and water quality are major concerns, and where agricultural production remains economically important. Maintaining or restoring mycorrhizal function in these regions supports both environmental and productive goals. The quantitative baseline provided by global mapping allows assessment of how different management or restoration approaches affect network recovery relative to regional benchmarks. This information can guide prioritization of conservation investments and evaluation of restoration success.

The concentration of mycorrhizal infrastructure in grasslands also highlights the broader consequences of ongoing grassland conversion and degradation. Each hectare of native grassland converted to intensive cropland represents a loss of mycorrhizal network capacity that is difficult and slow to replace. Conversely, each hectare of restored grassland offers the potential to rebuild a portion of that capacity while delivering co-benefits in soil carbon storage, water regulation, and habitat provision. These trade-offs underscore the importance of landscape-level planning that recognizes the outsized role of grassland ecosystems in supporting mycorrhizal-mediated soil functions.

Subsequent sections synthesize the full range of findings from the global mapping and mechanistic understanding of mycorrhizal networks to identify strategic priorities for research, policy, and management. Grassland and prairie systems occupy a central position in any such strategy because of both their current importance as mycorrhizal reservoirs and their vulnerability to continued loss. Protecting and restoring these systems offers one of the most efficient pathways for maintaining and recovering the planetary-scale biological infrastructure whose scale and functional significance have now been quantified.

11. Challenges, Uncertainties, and Future Research Directions

The 2026 global mapping of arbuscular mycorrhizal fungal networks represents a major advance in quantifying one of Earth's largest biological systems. At the same time, the study and the broader body of research on which it builds reveal significant challenges and uncertainties that must be addressed to fully realize the scientific and practical potential of this knowledge. These limitations span data coverage, mechanistic understanding, management applications, and the interactions between mycorrhizal networks and other global change drivers. Acknowledging

these challenges provides a realistic foundation for prioritizing future research and for interpreting current findings in policy and management contexts.

The global map itself contains important spatial and methodological limitations. While the underlying dataset of over sixteen thousand soil cores represents an unprecedented compilation, large regions remain undersampled, particularly in parts of the tropics, high-latitude grasslands, and certain arid zones. Predictions in these areas carry higher uncertainty, and the true distribution of network density may differ from current estimates. The mapping focuses exclusively on the upper fifteen centimeters of soil; deeper layers contain additional hyphal length and biomass whose contribution to total infrastructure and function remains poorly quantified. The study also addresses only arbuscular mycorrhizal fungi, leaving ectomycorrhizal and other mycorrhizal guilds outside its scope. Extending coverage to greater depths and additional fungal types will be necessary to develop a complete picture of belowground fungal infrastructure.

Uncertainties also persist in the functional understanding of mycorrhizal networks. While the physical mechanisms of aggregate formation and the role of glomalin in carbon stabilization are well established in principle, the rates and controls on these processes vary across soil types, climates, and fungal communities. The contribution of mycorrhizal pathways to long-term soil carbon storage, relative to other inputs and stabilization mechanisms, remains difficult to quantify at scale. Similarly, the extent and ecological significance of inter-plant signaling through common mycorrhizal networks continue to be debated, with laboratory evidence of chemical transfer not yet fully reconciled with field observations of community-level outcomes. These mechanistic uncertainties affect predictions of how changes in network density will translate into changes in soil function and ecosystem services.

Management and restoration applications face additional challenges. Inoculation can accelerate colonization on degraded sites, yet outcomes remain variable and depend on complex interactions among fungal strains, soil conditions, plant communities, and subsequent management. Scaling successful inoculation from experimental plots to landscape levels requires better understanding of propagule dispersal, competition with native fungi, and the minimum network density needed to deliver meaningful functional benefits. Transitions to regenerative practices that support mycorrhizal recovery involve economic and operational trade-offs that differ across farm types, regions, and market contexts. The time lags between implementation of supportive practices and measurable improvements in network density and soil function can complicate adoption decisions and policy evaluation.

Climate change and other global change drivers introduce further layers of uncertainty. Shifts in temperature and precipitation regimes are likely to alter the geographic distribution of suitable conditions for different mycorrhizal taxa and to change the balance between plant carbon

allocation and fungal activity. Elevated atmospheric carbon dioxide may increase plant carbon allocation to mycorrhizal partners under some conditions, while simultaneously affecting nutrient demand and soil microbial dynamics. Interactions with invasive species, altered disturbance regimes, and changing atmospheric deposition of nutrients add complexity. Predicting how these drivers will affect mycorrhizal networks at regional and global scales requires integrated modeling frameworks that currently remain underdeveloped.

Future research priorities emerge directly from these challenges. Expanding soil sampling coverage, particularly in undersampled biomes and deeper soil horizons, would improve the accuracy and resolution of global and regional maps. Development of standardized, cost-effective methods for monitoring network density and activity over time would support adaptive management and long-term assessment of restoration and regenerative transitions. Mechanistic studies that link specific fungal traits to soil physical and carbon outcomes under field conditions would reduce uncertainty in functional predictions. Research on the economics of mycorrhizal-supportive practices, including the valuation of co-benefits such as carbon sequestration and water quality improvement, would inform policy design and farmer decision-making.

Integration across disciplines and scales represents another important direction. Mycorrhizal networks interact with other components of the soil microbiome, with plant community dynamics, and with hydrological and biogeochemical cycles. Developing models that capture these interactions at scales relevant to both field management and Earth system processes would enhance predictive capacity. Collaboration between soil scientists, agronomists, ecologists, economists, and social scientists is needed to translate scientific understanding into practical strategies that are both effective and adoptable. Long-term, multi-site experiments that combine different management treatments with detailed measurements of network development and soil function would provide robust evidence for guiding transitions.

The challenges identified here do not diminish the significance of the global mapping breakthrough. Rather, they define the next phase of work required to move from improved description of mycorrhizal infrastructure to robust prediction and effective management. The scale of the networks documented in the 2026 study underscores the potential returns from addressing these uncertainties. Even partial progress in reducing key uncertainties could substantially improve the targeting of conservation investments, the design of regenerative systems, and the integration of biological soil processes into climate and agricultural policy.

Subsequent sections synthesize the current state of knowledge to identify strategic priorities that can guide research, policy, and on-the-ground action in the coming years. The combination of a newly quantified global baseline with explicit acknowledgment of remaining uncertainties creates a productive tension that can drive focused, high-impact research. By addressing the

challenges outlined here, the scientific community can build on the foundation established by the 2026 mapping to develop a more complete and actionable understanding of Earth's mycorrhizal infrastructure and its role in supporting soil health, ecosystem resilience, and carbon cycling.

12. Synthesis, Uncertainties, and Strategic Priorities for Soil Health

The 2026 global mapping of arbuscular mycorrhizal fungal networks has transformed the visibility of one of Earth's largest and most functionally significant biological systems. By combining extensive field sampling with machine learning and calibrated imaging, the study produced the first spatially explicit quantification of hyphal length, biomass, and carbon flux at a planetary scale. The resulting picture reveals networks of extraordinary extent whose distribution and functional contributions vary systematically across ecosystems and land-use types. This synthesis integrates the mapping results with established understanding of mycorrhizal mechanisms to identify both the current state of knowledge and the priorities that should guide future action.

The core findings establish mycorrhizal networks as a planetary-scale infrastructure with measurable impacts on soil physical properties, nutrient dynamics, and carbon cycling. Total hyphal length reaches approximately one hundred ten quadrillion kilometers in the upper fifteen centimeters of soil, with standing biomass containing roughly three hundred megatons of carbon. Annual carbon transfer through these networks moves approximately four billion tons of carbon dioxide equivalent into soils. These networks concentrate in grassland and wetland ecosystems, where they support high densities that contribute disproportionately to soil aggregation, water retention, nutrient acquisition efficiency, and long-term carbon stabilization. In contrast, intensively managed croplands exhibit substantially lower network densities, reflecting the cumulative effects of tillage and agrochemical inputs on fungal populations and soil conditions.

The functional mechanisms through which these networks operate are interconnected. Hyphal growth and glomalin production physically bind soil particles into stable aggregates, improving porosity, infiltration, and resistance to erosion while protecting organic matter from rapid decomposition. The same networks extend the effective root system for nutrient acquisition, particularly phosphorus, and enhance overall plant nutritional status and stress resilience. Carbon allocated by plants to fungal partners supports hyphal turnover and glomalin accumulation, contributing to both short-term nutrient cycling and longer-term soil carbon storage. These physical, chemical, and biological functions reinforce one another, creating integrated effects on soil health that exceed the sum of individual contributions.

Land management exerts strong control over network extent and function. Conventional practices of frequent tillage and high synthetic inputs have reduced mycorrhizal infrastructure across large areas, with corresponding losses in soil structural quality, nutrient retention, and carbon sequestration capacity. Regenerative approaches that reduce disturbance, increase plant diversity, and moderate external inputs create conditions for network recovery. Intentional inoculation can accelerate recolonization on severely degraded sites when combined with supportive management, although outcomes remain variable and depend on site conditions and follow-up practices. Grassland and prairie ecosystems, which currently harbor the highest network densities, represent both critical reservoirs of existing function and priority areas for conservation and restoration.

Significant uncertainties remain despite the advances represented by the global map. Spatial coverage is incomplete in several major biomes, and predictions carry higher uncertainty in undersampled regions. The mapping addresses only the upper soil layer and arbuscular mycorrhizal fungi, leaving deeper soils and other fungal guilds unquantified. Mechanistic understanding of carbon stabilization rates, inter-plant signaling significance, and species-specific functional traits contains important gaps. The interactions between mycorrhizal networks and climate change, invasive species, and changing disturbance regimes are only beginning to be explored. These uncertainties limit the precision of predictions about future network distribution and functional outcomes under different management and environmental scenarios.

Strategic priorities for research follow directly from these gaps. Expanding sampling coverage and developing cost-effective monitoring methods would improve mapping accuracy and support adaptive management. Mechanistic studies linking fungal traits to soil outcomes under field conditions would reduce functional uncertainties. Long-term experiments combining different management regimes with detailed measurements of network development would provide robust evidence for guiding transitions. Economic analyses that value the multiple co-benefits of mycorrhizal-supportive practices would inform policy design. Integration of mycorrhizal dynamics into Earth system and agricultural models would enhance predictive capacity at larger scales.

Priorities for policy and management center on protecting existing high-density networks and creating conditions for recovery where densities have declined. Conservation of grassland and wetland hotspots offers high returns for maintaining planetary mycorrhizal infrastructure and associated ecosystem services. In agricultural landscapes, support for reduced tillage, diversified rotations, cover crops, and calibrated nutrient management can accelerate network recovery while delivering benefits in soil health, input efficiency, and resilience. Restoration programs on degraded lands should incorporate mycorrhizal considerations, including inoculation where

appropriate and plant community choices that support fungal diversity. Policy frameworks that recognize the value of biological soil infrastructure can incentivize practices that protect and enhance mycorrhizal function alongside other environmental objectives.

The synthesis of current knowledge points toward an integrated approach to soil health that explicitly accounts for mycorrhizal networks as central biological infrastructure. These networks do not operate in isolation; they interact with plant communities, soil physical properties, nutrient cycles, and carbon dynamics to shape ecosystem outcomes. Management decisions that affect network density and connectivity therefore influence multiple soil functions simultaneously. Recognizing this integration allows for more coherent strategies that pursue soil health, agricultural productivity, water quality, and climate mitigation as interconnected rather than competing objectives.

The global mapping has made visible what had long remained hidden. The networks quantified in the study represent a biological system whose scale rivals major geological and atmospheric features and whose functions underpin critical ecosystem services. Protecting this infrastructure where it remains intact and restoring it where it has been diminished constitute strategic priorities for soil health in the coming decades. The uncertainties that remain should not delay action; rather, they should focus research and monitoring efforts on the most consequential gaps while management proceeds on the basis of current best understanding. The hidden mycorrhizal infrastructure of Earth is no longer invisible. The task now is to ensure that its protection and wise use become central to how societies manage soils and landscapes in a changing world.

13. References

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